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Small Robot Team System Design

By Stuart H. Young and Hung M. Nguyen

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14. ABSTRACT

Small robots, unmanned ground vehicles (UGV), unmanned aerial vehicles (UAV), and unattended ground sensors will be ubiquitous on the battlefield of the 21st century, principally to lower the exposure to harm of our ground forces in urban and open terrain. Teams of small collaborating physical agents conducting tasks such as reconnaissance, surveillance, and target acquisition intelligence, chemical and biological agent detection, logistics, decoy, sentry, and communications relay will have advanced sensors, communications, and mobility characteristics. The U.S. Army Research Laboratory (ARL) is conducting research in sensor fusion, communications, and processing on small mobile robotic platforms principally in the urban environment in support of Military Operations in Urban Terrain.

This report discusses ongoing research at ARL that supports the development of multirobot collaboration. Commercial all-terrain robotic vehicle and packbot robots from iRobot are being used along with advanced battlefield visualization tools and other tools to effectively command and control teams of collaborating robots and present the gathered information in a manner that is useful to the commander. The software architecture and the modular packaging designs will be the focus of the report, which also consider mother ship concepts. Additionally, work that has been conducted with Project Manager Soldier Systems to integrate robotic platforms with the Land Warrior ensemble will be discussed, as well as with the Objective Force Warrior program.

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Contents

List of Figures

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1. Introduction

The transformation of the U.S. Army toward an objective force that is more lethal, survivable, sustainable, and responsive to worldwide threats will include robotic systems. The Future Combat System (FCS) and Objective Force Warrior (OFW) are two critical initiatives leading toward the Objective Force that will include robotic systems. The U.S. Army Chief of Staff, General Shinseki stresses that soldiers will "remain the centerpiece of our formations" and will be the "heart" of the Objective Force (*1*). The U.S. Army Research Laboratory (ARL) is developing technology that supports the FCS and the soldier-centric OFW initiatives. For OFW 2010, there is an immediate need for a robotic follower within the next 2–3 years. OFW focuses on extending small team capabilities without overburdening the warrior (this will include robotic systems) (*2*). This report will discuss some of the work that ARL is doing with the Land Warrior (LW) program and the OFW Program.

With robots being ubiquitous on the battlefield of the future, it is necessary for a robotic architecture that will encompass many of the aspects of the interaction between soldiers and robots. The system design presented in this paper takes many aspects of existing hierarchical and reactive robotic paradigms (*3*) and existing command and control (C2) applications (such as two-dimensional [2-D] and three-dimensional [3-D] visualization) to create a hybrid architecture that is usable by multiple agent teams, as well as soldiers at different levels to control the robots on the battlefield.

For example, a team of n-robots may be controlled from the rear by a few soldiers in a C2 vehicle, a tactical operations center (TOC), or from another part of the world. In addition to the robots on the ground, soldiers (wearing LW systems) may be operating in the same area. And, it may be necessary, desired, or required for the soldiers (presumably light forces for this example) to communicate with or take control of the robots operating in their area. In order to accomplish this, the architecture on the robot must be compatible with the rear command and control vehicle as well as with the small limited computers that the soldiers may be wearing or have with them. Additionally, the robots controlled from afar may carry smaller robots that are specifically more useful to ground soldiers and may deliver smaller robots or other equipment to an area. This paper will address in more detail, the system design that incorporates multiple levels of control of multiple robots, including collaboration between robots and robots acting as mother ships for other robots or soldier's (Multi-function Utility Logistics Equipment [MULE]).

This report also discusses several experiments in which 1–3 robots were controlled by a single operator to conduct reconnaissance, surveillance, and target acquisition (RSTA) missions to include the detection of acoustic events, namely gunshots and other loud acoustic events, and conduct surveillance of moving targets using visible and infrared (IR) sensors. Results from field experiments conducted at Ft. Knox, KY and Ft. Bragg, NC will be presented.

2. System Architecture

The system architecture presented here evolved out of the need to control multiple robots from multiple echelons. As discussed previously, robotic systems need to be controlled from the rear, or perhaps a C2 vehicle. In order to accomplish this, we tied the control of the robots to our 2-D DII/COE (or Combat Information Processing [CIP]) mapping application and to our Virtual Geographical Information System (VGIS) 3-D visualization application. Both of these applications have been widely used on several U.S. Army Intel programs.

Similarly, we needed to be able to control the robots from the individual soldier. The soldier can currently control the robots using teleoperation and semi-autonomous waypoint navigation, and in the future, the architecture can accommodate fully autonomous robots. The system supports multimodal input including the following: text, joystick, speech, and waypoint designation. This leads to the integration with the LW System. We integrated thin-client applications onto an LW training system in order for the LW System to control multiple robots. By adding thin clients to the LW System, we are able to take advantage of the processing onboard the robot and not burden the limited processing capability of the LW System. This is discussed in the Ft. Knox and Ft. Bragg experiments. We demonstrated this control from a Bradley Fighting Vehicle (Scout Warrior), and from a light infantry soldier wearing only an LW System.

2.1 Software Application Architecture

The testbeds ARL is using for the research presented in this paper are commercial off-the-shelf (COTS) robotic mobility platforms (ATRV-2, Urban Robot, and Packbot) from iRobot (formerly IS Robotics and Real World Interface [RWI]). The robots are subsequently outfitted with various sensors such as an acoustic array, visible and IR cameras, and an anemometer meteorological sensor and include the ARL robot control software to perform the RSTA tasks.

The software architecture of the Robot Team Agent follows the client/server software model approach. It is a message-based and modular infrastructure that is designed to provide usability, flexibility, interoperability, and scalability.

The ARL Robot Control Software package is a defined suite of software modules and application programmer interfaces (API) with multithreaded reconnect capability, using pthreads (*4*). Some software modules, like the RobotAgent and the LocationAgent are connected to the robot motors and wheel encoders through the RWI CORBA 2.0 compliant hardware servers (*5*) to control the robot movement and to inquire the robot local location x,y. Communication between the ARL software modules is based on the ARL dynamic distributed processing infrastructure using CIPNET and the Agent Registry services (*6*).

2.1.1 CIP Interprocess Communication

The Robotic Control Software shares the same common networking services that exist within the ARL CIP 2-D display software and the VGIS 3-D display software. These network services provide an intertask communications protocol to isolate applications from the system specific interprocess communications. The network is logically separated into three layers: CPU/Chassis,

Local Area Network (LAN), and Wide Area Network (WAN). A CPU/Chassis consists of only one logical CPU and a backplane of peripherals. If there are multiple physical CPUs available, it is assumed that the operating system (OS) will make this transparent, using symmetric multprocessing. At this level, the intertask communications is implemented using Unix's interprocess communications (IPC) standard. A LAN consists of a group of CPU/Chassis's logically connected by ethernet (TCP/IP). A WAN consists of a group of LANs logically connected by various physical media, such as radio frequency (RF) links, ethernet, or RS-232 serial. A task is a program running on a CPU/Chassis participating in the network. Every task has a unique assigned identification number (taskid) defined at run time. Taskid's will be bound at run time to symbolic names (taskname). All tasknames must be unique within one of the following scopes:

- **LOCALTASK** - The task is a server whose name is only known within the local CPU OS.
- **GLOBALTASK** - The task is a server whose name is known inside and outside of the CPU to a group of logically grouped hosts (tied together by a CIPLANSERVERHOST).
- **WORLDTASK** - This is similar to the GLOBALTASK except that the server name is known across multiple CIPLANSERVERHOST groups. CIPLANSERVERHOST is the system environment parameter that stores the host computer name where the CipNameServer process is running.
- **CLIENTTASK** - The task is a client whose name is unknown everywhere. The task will have an unpublished listening port. The task will make all its connections by using netOPEN (*6*) to a server.

2.1.2 Agent Registry Services

Limitation from the CIP interprocess communication networking services arises when similar tasks with same names are running on multiple robots. To encompass this problem, the CIP Agent Registry Services (*6*) is used. The Agent Registry is an idealized database that holds information regarding the services that all registered agents offer to other agents in the network community. Agents reference the Agent Registry when trying to find the identity of another agent that will provide a needed service. Although the Agent Registry makes no guarantees that a recommended agent is currently instantiated on the network, the current implementation requires the agent to self register, and therefore the actual existence of a particular agent is probably very high. In theory, the agent registry function only helps one agent find the identity of another agent that best meets a service requirement. The agent AregServer is a C++ process that implements the registry database. The registry server is implemented as a layer on top of the CIPNET process name service where one master registry exists in the WORLDNAME scope of the network and optional slave registries can be invoked as clients to the master. Each slave registry MUST have a unique agentName/hostName identification because the slave registry agents use the same registry client API as any other agent in the system.

2.1.3 Robot Control Software Agents Description

The following paragraphs describe the software agents in the system and their functions (Figure 1):

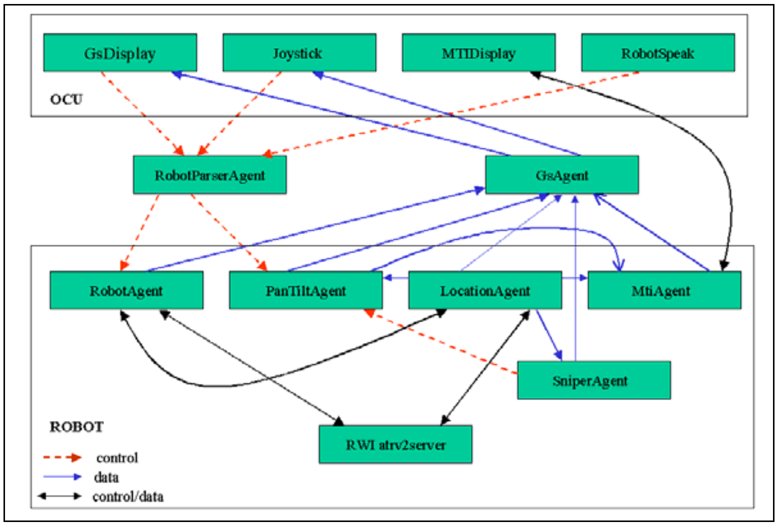

Figure 1. Network control/data flow diagram.

Robot Device Controllers–Low-level status and control of sensors and robot mobility: compass, global positioning system (GPS), sonar, mobility, pan tilt, sniper detector, moving target indicator Image server.

Robot Servers related Agents

- RobotAgent - controls the robot mobility via the RWI hardware servers
- PanTiltAgent - controls the pan tilt device
- LocationAgent - provides the robot position (lat/long) and compass heading
- MtiAgent - locates and tracks moving objects in a sequence of images from a stationary camera
- SniperAgent - listen to acoustic event on IPC Socket and send control command to the pan tilt server

Gateway - Provides fusion point between controllers and Operator Control Unit (OCU) or Ground Control Station agents

- gsAgent - collects and fuses data from Robot Device Controllers (except for MTI) for analysis and display by various OCU station agents
- RobotParserAgent - accepts control commands from OCU agents and sends commands to appropriate controller(s)

OCU Station Clients Agents – Provides robot's status display and multimodel I/O control

- GsDiplay
  - Displays data received from gsAgent
  - Provides keyboard input window dialog to type text string commands and simple menu bar graphics user interface (GUI) to control pan tilt and robot mobility via the RobotParserAgent
- LittleJoy - reads joystick and sends pan tilt and robot mobility
- MtiDisplay - receives and displays images received from MtiAgent
- RobotSpeak - uses the Microsoft Speech Engine, receives voice commands from microphone and sends to the RobotParserAgent to control the pan tilt and robot mobility

The Multi-robots control/data flow diagram, shown in Figure 2, showed the scalability of the ARL robot control software infrastructure. It also showed that the bottlenecks could happen at the RobotParserAgent and GsAgent. This should not have any impact if the number of robots is less than eight. Future implementation will be concentrated on improving the design to allow multiple copies of RobotParserAgent and GSAgent to run and add the dynamic routing connection capability from the OCUs to the RobotParserAgents and GSAgents based on the network traffic to those agents.

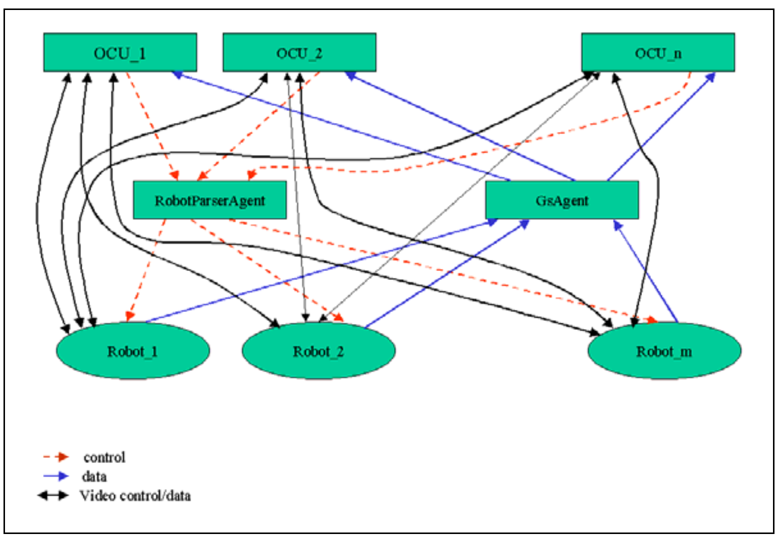

Figure 2. Multi-robots control/data flow diagram.

In this configuration (Figures 3 and 4), the robots are interfaced to the 2-D/3-D map display modules. The 2-D-CIP maps application window is displayed on one of the touch-sensitive flat panels, and the 3-D-VGIS maps application is displayed on the other. This set up provides the capability for users to collaborate in selecting control waypoints from the 2-D/3-D application windows to define the route for robots to perform the RSTA operation. Current obstacle avoidance capability of the robot is limited to the simple guarded-motion algorithm from RWI

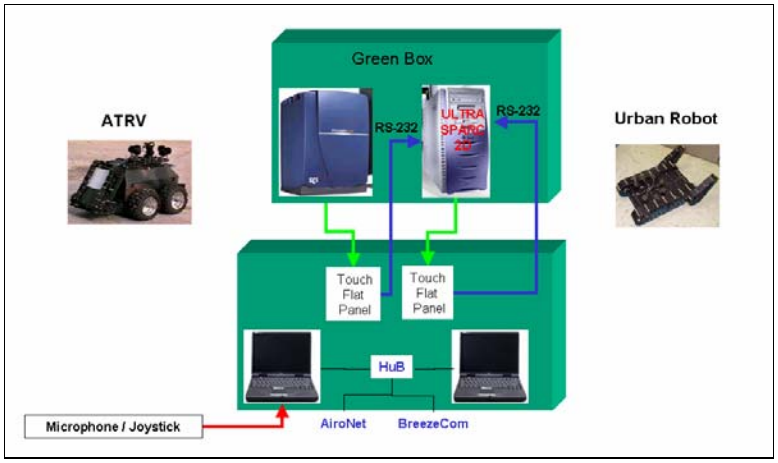

Figure 3. Autonomous asset controller configuration.

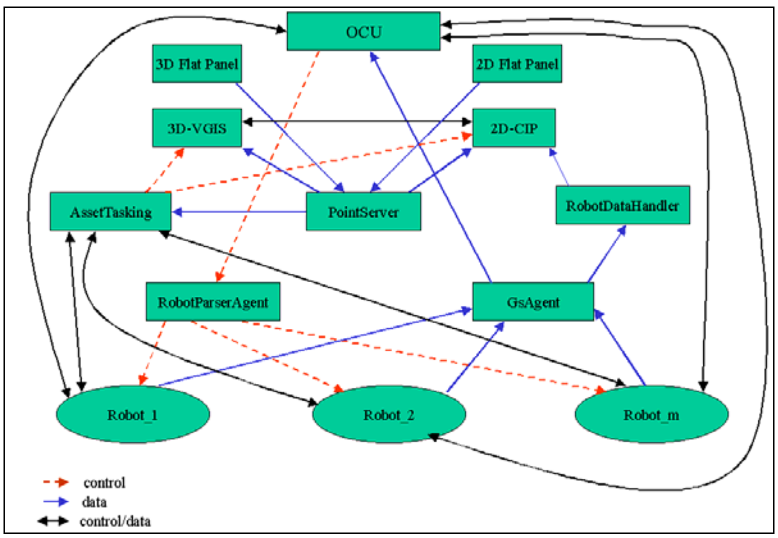

Figure 4. Autonomous asset controller diagram.

using sonar and laser system sensors. Sophisticated route planning and reactive behaviors are currently being implemented onto the robots to provide better autonomous to robots.

2.2 Hardware Architecture

As mentioned previously, the testbeds that ARL is using for the research presented in this paper are COTS robotic mobility platforms from iRobot (Somerville, MA) outfitted with commercially available RSTA sensors. ARL is using three ATRV-2 robotic platforms that have several limitations for our testing with soldiers, which is the topic of this section. In addition to the ATRVs, we have an Urban Robot that can “dock” onto the ATRV, and are currently integrating Packbot robots from iRobot. These two smaller robotic platforms came out of the Defense Advanced Research Projects Agency (DARPA) Tactical Mobile Robotics (TMR) program.

We have developed a design for a modular robotic sensor platform that replaces the existing sensor platform for the ATRV-2 robotic platform. Our design addresses many of the shortcomings of the existing platform for our testing needs and facilitates experimentation with U.S. Army soldiers and other field experiments. We have designed a modular hardware design that facilitates changing sensors and components for our experimentation with soldiers in the field. Additionally, our platform resists dust, rain, and other environmental effects that the existing system doesn't. Some of our testbeds are shown in Figures 5 and 6. The larger ATRV-2 robot shown in Figure 5 is outfitted for an RSTA mission. The sensors in Figure 5 include the following: visible camera, IR camera, laser rangefinder (LADAR), weather sensor, stereo camera pair, sound navigation and ranging (SONAR), GPS, a digital compass, and an acoustic array. The modular design also considers future testing, which includes different missions like a logistics mule, communications relay, or different sensing. In addition to the sensors, we have multiple processors onboard the robot for sensor fusion and detection as well as providing services to the thin clients on the LW Systems. We are currently integrating several of the RSTA sensors onto the Packbot platform shown in Figure 6. These sensors include an acoustic array, a visible camera, and an IR camera. Additionally, the design allows for transporting the smaller Packbot robot to facilitate mother ship experiments.

Figure 5. iRobot ATRV-2 robot with improved modular sensor platform.

The original iRobot ATRV-2 was not designed to be used outdoors in adverse weather and harsh environments. Additionally, it is not as modular as we needed to rapidly change components in experimental environments with soldiers. It is not water resistant for operations in the rain and snow. It was also not protected from dusty and dirty environments. Both of these shortcomings have caused computer components and sensors to fail during previous experiments. The past design is not modular and is currently configured for an RSTA mission with an 8-microphone acoustic array, a visible camera, an IR camera, 12 sonar sensors, 3 CPUs, 1 wireless LAN, a video transmitter, a GPS sensor, a digital compass, and a driving camera. It is used to detect gunshots and loud impulsive noises in an urban environment and to perform image motion

Figure 6. iRobot Packbot.

tracking using both cameras. The robot has been used at experiments with U.S. Army units, at DARPA Tactical Mobile Robotics (TMR) Program experiments, and recently with the U.S. Army's LW System to demonstrate soldier/robot interaction and experimentation.

The improved modular sensor platform presented here is focused on conducting RSTA missions, primarily in urban environments. The present design is modular enough to accommodate other sensors, but it is currently configured with an 8-microphone acoustic array, a visible camera, an IR camera, a scanning LADAR, a point LADAR, 12 sonar sensors, 3 CPUs, 2 wireless LANs, a video transmitter, a GPS sensor, a digital compass, a weather sensor, a stereo camera pair, and a driving camera. This design includes previous functionality, plus the ability to detect and track vehicles acoustically and visually; navigate using waypoint navigation as well as teleoperation; act as a communications relay; allow smaller robots (Packbots) to dock; as well as many other advancements, applications, and capabilities. This platform is currently being used to demonstrate soldier-robot interaction with the current and future LW Systems and ARL, Human Research and Engineering Directorate (HRED). Additionally, this platform will be used during experimentation of multiple robotic physical agents, demonstrating collaborative control and data fusion. Also, experimentation of processing and communications on small robotic systems will be conducted. Figure 7 shows an alternate improved modular sensor platform design being developed.

In the future, the design will be upgraded by simply adding/exchanging some component modules or by exchanging entire mission packs. The modular design provides the ability for the ATRV-2 to act as mother ship for smaller packbot (and FCS soldier unmanned ground vehicle [SUGV])-sized robots. For example, the robot can recharge depleted batteries on smaller Packbots (increasing mission duration), can carry Packbots (increasing mission range), can fuse information from multiple robots (increasing processing capability), and can act as a communications relay/uplink. Additionally, the design is flexible enough to allow the introduction of a module that can launch a micro-UAV and receive data from it. The design allows for a module that can deploy numerous unmanned ground sensors to the battlefield or other mission locations. Furthermore, the modular design provides the capability of acting as a logistics robot (LOGBOT) that can recharge batteries for existing soldier needs, like a platoon of soldiers wearing LW Systems and other necessary battery requirements. The design allows for

Figure 7. Model of Modular Platform.

the introduction of a future hybrid-electric power system where a generator is added to the existing batteries, allowing for longer mission durations. The introduction of fuel cells is another possibility for future onboard power generation. Future planned uses include mapping the interior of buildings with the robots and communicating that information back to other robots for distributed fusion and collaboration, or back to commanders. Also, a communications module is under development where the robot will be transitioned from an RSTA mission to a communications relay, and several robots will act as a remote distributed antenna array. The future introduction of a chemical/biological agent detector to the robot's suite of sensors will be used to keep soldiers out of harm's way. The docking module may be replaced with a module that deposits unattended ground sensors and may retrieve them (or other robots) with a retriever/manipulator arm module. Additionally, any of the modules can stand alone or be placed on other platforms by just applying power.

3. Experimental Results

Here we discuss two experiments that demonstrated the architecture presented in this report. Results from field experiments conducted at Ft. Knox, KY and Ft. Bragg, NC are presented here.

3.1 Ft. Knox, KY

The first experiment that we will discuss occurred in May 2001 at Ft. Knox, KY. At this experiment, we demonstrated the Scout Warrior concept. We outfitted a tank commander in a Bradley Fighting Vehicle with a modified LW System to control the robot that was deployed out of the Bradley with the scout soldiers. This experiment and demonstration was conducted at the Armor Conference with the LW program office and Exponent of Phoenix, AZ. Figure 8 shows the robot in a Bradley, and Figure 9 shows the Scout Warrior Team.

Figure 8. Robotic Scout in Bradley Fighting Vehicle.

Figure 9. Scout Warrior Team.

LW (*7*) is the U.S. Army's program for integrating the infantry soldier into a battlefield digital communication system that is optimized for close combat. The LW has several subsystems: the weapon, integrated helmet assembly, protective clothing and individual equipment, computer/radio, and software. ARL collaborated with Exponent to interface the LW training system with the ARL robot system for demonstration at Ft. Knox.

Exponent provided the LW map display server software with the modification to display the robot symbol on the map accordingly with the robot GPS location. Additionally, Exponent built the Gatewayserver that receives user datagram protocol (UDP) data from GsLW and MtilW and sends them to Exponent groundstation and other LW Systems for display (see Figure 10).

ARL developed and modified several software components. The gsLW, which accepts data from the GsAgent, filter and forwards them via UDP to ExponentServerGateway. The mtiLW receives and displays images from MtiAgent and transmits image data by either copying them to a bmp file and sending the filename on to a UDP channel or by sending the raw image on the UDP. The LwSim receives an image for display from mtilw on the UDP channel. LittleJoy reads joystick and sends pan tilt and robot mobility commands to RobotParserAgent. This is a modification of the Joystick program to support a smaller joystick on the LW's USB port. The Mobility/PanTilt Graphic User Interfaces – sends robot pan tilt and robot mobility commands

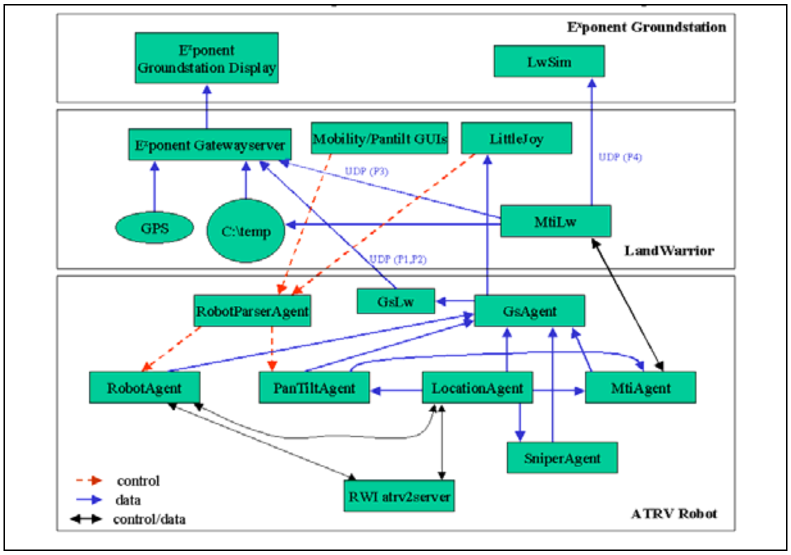

Figure 10. LW configuration control/data flow diagram.

from simple GUIs displayed on the LW touch sensitive tablet display. Four types of UDP packets were used as follows:

- Type 1(TrackPacket): robot_ID, robot_longitude, robot_latitude, robot_heading
- Type 2(SniperPacket): robot_ID, sniper_longitude, sniper_latitude, sniper_heading
- Type 3(image filename): image is stored in c:\temp\mti*.bmp and the filename is sent to Exponent Gateway server as UDP type 3.
- Type 4(image): image bitmap

The ARL/Exponent integration provided the enhanced capability to LW to wirelessly tele-operate the robot and control the camera motion from a safe location. The robot was used to watch an area of interest. Imagery acquired from the robot's visible and IR cameras can be viewed on the enhanced LW display tablet and then can be transmitted back to the ground control station and other LW Systems.

3.2 Ft. Bragg, NC

The second experiment that we will discuss occurred in July 2001 at Ft. Bragg, NC. At this experiment, we demonstrated the Robot Warrior concept with the LW system. We outfitted a light infantry soldier with an LW training system to control the robot. Figure 11 shows the soldier controlling the robot, and Figure 12 shows the Robot Warrior with the LW fire team.

In this experiment, the configuration was essentially the same as in the Ft. Knox demonstration except that a single light infantry soldier outfitted with an LW training system controlled the robot. The soldier was able to control the robot's movement, sensors, and communicate with his squad. Due to processing constraints, the soldier controlling the robot was the only one able to see what the robot detected. However, the architecture supports the images from the robot being sent to all of the squad members, and this capability will be implemented into future variants of the LW System.

Figure 11. Robot with LW-equipped soldier.

Figure 12. Robot with LW-equipped soldiers.

4. Conclusion and Future Work

The system architecture presented in this paper demonstrates the multi-echelon control of multiple robots and a modular hardware approach to accommodate experimentation. Ongoing work shows the control of multiple robotic platforms from a soldier wearing an LW System, and from a more capable (2-D/3-D map display, processing, and communications) C2 platform. Upcoming field experiments will test the control of up to five robots in the field at Adelphi, MD, Blossom Point, MD, and at Spesutie Island, Aberdeen Proving Ground, MD. During these experiments, we will use both single soldier and C2 platform control in the field of the software

described in this paper that has been demonstrated in the laboratory. Also, we will be collecting data for ongoing work for collaboration between several robots and sensor fusion from multiple points of view (*8, 9*). This collaboration includes integrating UAVs and Unattended Ground Sensors into the overall system, which can cue the ground robots.

Additionally, we are currently involved in integrating the control of ARL robot testbeds with the OFW program and with future variants of LW Systems. During this integration, we will incorporate voice control of the robots, waypoint control of the robots using the LW map display, tactile glove input, and integrated soldier weapon control of the robots.

Future work also includes integrating several of the RSTA sensors from the ATRV platform onto the Packbot platform. Specifically, ARL is working with iRobot to integrate acoustic sensors, IR imaging sensors, and RSTA processing onto the packbot (*10*). The ATRV robots can then carry these Packbots, and mother ship (marsupial) experiments are planned to continue, including autonomous docking and charging.

Finally, ARL is working with the PM Soldier office and Natick Soldier Center to develop a prototype robotic MULE targeted for the OFW program. The desired concept is to apply limited robotics and teleoperation to an M-Gator platform with LW connectivity and interface. The proposed M-Gator will be controlled using an ARL-developed, soldier-worn universal robot controller that integrates weapon control, glove control, speech control, and waypoint control. The M-Gator provides the LW System advanced processing capability, memory capability, and smart battery charging. It can also provide a LW squad with water purification, equipment carrier, communications relay, and act as a mother ship for robots (like Packbots) for use by the LW squad.

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